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SOVIET PROGRESS IN PHYSICS: Reviews of Current Research

Simon Kassel (Editor)

A Report prepared for

ADVANCED RESEARCH PROJECTS AGENCY

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10. ABSTRACT

Soviet physicists claim significant results in a number of specialized research areas. The primary purpose of the work on generation and relatively long-term maintenance of plasma at atmospheric and higher temperatures appears to be achievement of controlled thermonuclear reactions; a secondary goal could be damage to materials in strong radiation fields. Study of explosive electron emission and high-vacuum insulating properties is significant for space applications, especially where high currents and voltages are involved. The design of low-inductance heavy pulse current generators and their application to the production of strong magnetic pulses probably will contribute to achievement of controlled thermonuclear reactions, as well as to metal forming, space propulsion, and other secondary goals. Additional research includes work on the use of laser emission to obtain superconductivity at elevated temperatures and a comprehensive analysis of the diamagnetic moment that appears in plasma produced by laser-induced breakdown.

11. KEY WORDS

Physics
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PREFACE

This Report has been prepared within the scope of the exploitation of Soviet scientific and technical literature program sponsored by the Advanced Research Projects Agency.

Current research of leading Soviet physicists is of considerable interest in shedding light on significant R&D areas being explored in the USSR, their topical priorities in research efforts, and perhaps to some extent, their research goals. An insight into these factors is enhanced if one examines a given activity in terms of an orderly progression of research reports spanning an appreciable period of time, the extent and consistency of teamwork within the activity, and its relation to other similar efforts.

Recent examples of such systematic activities are reflected in this brief outline of five Soviet efforts in physics; their significance in advancing knowledge may vary considerably; nevertheless they all appear to be current, on-going, and major preoccupations of their individual authors.

These reviews were prepared by S. Kassel, of The Rand Corporation; S. G. Hibben and A. Polushkin, of Informatics, Inc.; and Y. Ksander, a consultant to The Rand Corporation.

SUMMARY

Soviet physicists claim significant results in a number of specialized research areas. Groups of related publications pertaining to each area have been examined and reviewed in turn.

Generation and relatively long-term maintenance of plasma at atmospheric and higher pressures are the topics researched at the Institute of the Problems of Mechanics and the Physics Laboratory, both of the Academy of Sciences, USSR by Yu. P. Rayzer and P. L. Kapitsa, who approach the same goals by different techniques. The primary purpose of this work appears to be controlled thermonuclear reactions although there may be other applications; a secondary goal could be damage to materials in strong radiation fields. No true fusion reaction has been reported, although the current results seem encouraging enough to warrant a steady and systematic activity.

A large effort in the study of explosive electron emission has been continued by G. A. Mesyats of the Leningrad State University. The high-vacuum insulating properties are significant in application to outer space especially where high currents and voltages are involved.

The work of G. A. Shneyerson at the Leningrad Polytechnic Institute deals with the design of low-inductance heavy pulse current generators and their application to the production of strong magnetic pulses. Again the primary goal is the achievement of controlled thermonuclear reactions, with a broad array of secondary goals that include metal forming, space propulsion, etc.

Superconductivity has long been an object of steady and relatively intense research in the Soviet Union. A novel and interesting approach to obtain this effect at elevated temperatures is reported by V. D. Blazhin and A. S. Selivanenko who apply laser emission for this purpose.

Finally, the production of plasma by laser-induced breakdown is treated in an original manner by G. A. Askar yan of the Lebedev Physics Institute known for his radical approach to many problems of quantum electronics. In the most current series of papers Askar'yan developed a comprehensive analysis of the diamagnetic moment that appears in such plasma.

CONTENTS

I. GENERATION OF PLASMA IN FREE AIR

S. Kassel

For a number of years the noted Soviet physicist, Yu. P. Rayzer, has been increasingly active in theoretical and experimental research on plasma generation at atmospheric and higher pressures. The research has been carried on at the Institute of the Problems of Mechanics, Academy of Sciences, USSR. In the course of this work Rayzer investigated the inductive discharge and gas breakdown by ruby, neodymium glass, and CO_2 laser beams. In a number of papers Rayzer stated that his objective is the invention of CO_2 laser powered "optical plasmotron," a device, in Rayzer's words, "of considerable fascination" [1]. A plasmotron in Soviet usage is basically a form of a high-temperature torch, and in its conventional application is a fairly narrow concept to fascinate a scientist of the stature and interests of Rayzer. However, he also noted elsewhere [2] that the aim is the creation of a stable spatially localized plasma in free air and the increase of the size of such a plasma. At this time "the problem...is essentially reduced to that of the laser power feeding the plasma." He further says that it is now possible also to consider moving the plasma bunch in free air at will by moving the sustaining laser beam.

Such a concept would transcend the ordinary applications of the plasmotron device. Another interesting aspect of this research is furnished by Rayzer's statement that his work is related to the series of experiments performed by P. L. Kapitsa who produced a long-duration plasma with a very high temperature by an intense RF discharge in gas at atmospheric pressure. Kapitsa's experiments were the subject of last year's meeting of the Committee on Inventions and Discoveries of the Council of Ministers, USSR, and his results were declared to constitute a major scientific discovery [13].

Rayzer's own work in this area has been marked by a fairly systematic effort by himself and others associated with him of the above institute, indicating a steady progression of theoretical development and experimental verification of theory.

In 1965 Rayzer developed a general hydrodynamic theory of a supersonic light absorption and gas heating wave, computed the experimental

temperature of the wave, and considered three mechanisms of rapid spark propagation: detonation, radiation, and breakdown [3].

In 1968 Rayzer noted that high powers of laser emission used in laser spark experiments are necessary only to effect the gas breakdown and not to maintain the spark itself. If the plasma is initially created by an external source, further propagation of the laser spark in the optical detonation mode can proceed at power levels 2 orders of magnitude lower than those necessary for the gas breakdown. If the optical detonation mode is replaced by what is called the "slow combustion" mode, i.e., subsonic propagation of the discharge against the beam by the heat-conduction mechanism, the laser maintenance power can be lower still [4]. Rayzer's subsequent publications [5,6] were based on the combustion theory as a basis for an explanation of the high-frequency discharge in a flowing gas which, according to Rayzer, is the principle of operation of the electrodeless plasmotron. In this device cold gas flows in a tube through a solenoid which contains a stationary high-frequency discharge. A continuous plasma jet at atmospheric pressure emerges from the tube. The combustion analogy was also applied to the explanation of new phenomena of the laser spark type. Bunkin, Prokhorov and others [7] observed slow propagation of spark in atmospheric air. A beam of high-power, free-running neodymium laser was weakly focused by a long focus lens delivering light intensity of the order of 10 Mw/cm^2. The intensity was insufficient for optical detonation whose threshold under this condition is equal to 100 Mw/cm^2. However, with a pulse energy exceeding 730 j the laser spark appeared and expanded symmetrically about the optical channel at the rate of less than 50 m/sec. It was assumed that the mechanism of propagation is the ordinary thermal conductivity where the front runs along the moving gas as in combustion in a pipe with a closed end.

Rayzer's key theoretical paper [5] on the flowing-gas discharge was published in 1968 (submitted to the editor on January 24, 1968). In this paper he formulated an approximate theory of the inductive discharge in a flowing gas and established a formal analogy between slow propagation of discharge maintained by absorption of electromagnetic energy, on the one hand, and combustion, on the other. The theory was applied to the specific case of a simple plasmotron device built by M. I. Yakushin at

the Institute of the Problems of Mechanics, in which argon or air at atmospheric pressure flowed through a quartz tube at a velocity of 1 m/sec. The tube was inserted into a solenoid where a 15 MHz electric discharge in the gas flow heated it to 10,000-12,000°K. For a final temperature of the discharge ranging from 7,000° to 12,000°K, the power delivered ranged from 8.5 to 54 Kw for air and from 0.4 to 31 Kw for argon. The gas flow was from 260 to 680 cm^3/sec for air and from 62 to 1500 cm^3/sec for argon.

The theoretical concept of the plasmotron was further developed by Rayzer in a paper [8] published in 1970 (submitted to the editor on December 26, 1969), who this time proposed a cw CO_2 laser as the energy source.

Again, the problem was reduced to the determination of minimum required light power and plasma temperature. Plasma was assumed to be initially produced by an external source. The theoretical computation showed that to maintain plasma continuously in atmospheric air at about 18,000°K by means of a CO_2 laser, the required power is about 7 Kw. Rayzer considers this an imposing figure, but not unrealistic. The discharge could be ignited practically anywhere using mirrors and lenses to feed the energy. He expected that plasma would be easy to localize (to stabilize the flame) by focusing the beam. At high pressures the power required would be much lower (it can be varied also by choosing different gases), but the construction of the plasmotron would be in this case obviously more complicated.

At the same time Rayzer submitted [1] the results of a detailed theoretical investigation of the "slow combustion" process underlying the subsonic propagation of a laser spark and its application to the optical plasmotron. He concluded that the 7 Kw required for the maintenance of plasma in atmospheric air at approximately 18,000°K can be reduced to 2 Kw by a sharply focused CO_2 laser beam. In his theoretical paper Rayzer noted the interesting possibility to move the plasma bunch by moving the focal spot of the laser beam. Such a motion, however, would be limited in speed to the velocity of propagation of the discharge which is of the order of 2.4 m/sec.

The first successful experimental verification of the foregoing

theory was reported by Rayzer in May 1970 [2]. Rayzer obtained a continuously burning plasma "out of contact with any surfaces of the confining vessel." He used a Lund-100 industrial laser whose power was boosted to 150 watts. The discharge current in the laser was 100 ma, and the beam diameter was 2 cm. The breakdown gas was xenon at pressures up to 10 atm with an optimum at 3.5 atm. The laser beam directed into the gas was focused in the center of the vessel to a focal spot 0.1 mm in diameter. The stationary discharge was obtained by means of another CO_2 laser operating in a Q-switched mode, and yielding 10 Kw pulses 0.3-1.5 μsec long with from 50 to 250 Hz repetition frequency. The maintaining and igniting laser beams were arranged at right angles and their focal regions were made to coincide. The breakdown plasma existed for up to 10 μsec after each pulse and its dimensions were considerably smaller than those of the stationary plasma. The ignition system as used was admittedly not suitable for practical applications because of its relative complexity, but was very convenient for experimentation. The stationary plasma obtained in this manner was very stable and could last as long as 10 minutes or more. It was terminated either by the degradation of the maintenance laser which was driven near threshold, or to avoid strong overheating of the gas cell which was not cooled. Stable burning in xenon under experimental conditions was observed at pressures of 3-4 atm. Below 3 atm the discharge failed to ignite. The plasma temperature was about 14,000°K.

In his report, Rayzer again referred to the possibility of moving the plasma by swinging the maintaining beam of the CO_2 laser. He also at that time referred to Kapitsa's "ball lightning" and noted that the two experimental efforts were related.

In 1950 Kapitsa built a high power radio frequency oscillator which he called a planotron and which represented a kind of linearized magnetron [9]. It generated a power of several Kw at a wavelength of 10 cm. The emission induced a stationary discharge in helium at 10 torr in an enclosed vessel. The helium discharge had sharp boundaries and resembled a ball lightning; it lasted several seconds and had to be turned off because of overheating of the quartz vessel. This was the experiment that led to the development of the ball lightning theory based on the

assumption that the phenomenon is maintained by microwave radiation generated in storm clouds and serving as the energy source. A few years later Kapitsa developed a more powerful cw oscillator which he called the "nigotron" and used to continue his work on the hovering discharge in helium. Similar discharges were also obtained in argon, CO_2 and air. It was found that the shape and the degree of brightness of the discharge depended on the presence or absence and the amount of admixtures introduced into the gas. The best results were obtained with acetone whose admixture imparted a spherical form to the discharge and a blindingly white brightness. The shape of the discharge was also found dependent on the input power. At high input powers the discharge quickly assumed an elongated form which was most pronounced in hydrogen and deuterium at high pressures. Throughout the research cycle Kapitsa noted the exceptional stability of the discharge. Spectral analysis showed the electron temperature within the discharge sphere may exceed half a million degrees. This prompted the author to replace hydrogen by deuterium in order to test the possibility of neutron emission. Although the presence of neutrons was established with statistical reliability their thermonuclear origin was doubtful, even though the input power was increased up to 20 Kw. The author concluded that he was dealing with a hot plasma suitable for further CTR experimentation.

This was continued by building a toroidal resonator, in which the discharge was stabilized by mechanical rotation of the gas, to allow higher input powers to the discharge. In this configuration the string discharge was considerably lengthened and the input power was brought up to 40 Kw. At the present stage of this research the author assumes his plasma is hot; the electron temperature reaches the order of 1,000,000°K while the ionic temperature may be considerably lower. The problem of increasing the ionic temperature in the discharge to a level required for a reliable controlled thermonuclear reaction is being considered. The nigotron used in these experiments can now provide a continuous power reaching 175 Kw. It oscillates at frequencies corresponding to a wavelength of 19.3 cm in the H_{01} mode.

The Physics Laboratory of the Academy of Sciences, USSR, is a small facility in which the work is carried out on a relatively small scale. According to the author at this time the basic and one of the

more interesting problems in the study of the string discharge is the determination of ionic temperature.

Rayzer's experiments with CO_2 lasers continued and included a variation where he used a single flowing CO_2-N_2-He laser in a Q-switched mode to break down the gas and maintain a stable plasma [10].

In cw operation the laser delivered up to 70 w. The pulses had a repetition frequency of 50-250 Hz, at a peak power on the order of 10 Kw and a duration of 0.3-1.5 μsec. The gases were investigated at pressures up to 25 atm. In xenon where the measurements were the most reliable the minimum light intensity threshold was 150 Mw/cm^2 at 15 atm.

The most comprehensive series of experiments were published by Rayzer in December, 1970 [11] (submitted to the editor on July 8, 1970). In a sense, this work was further removed from the immediate application to air at atmospheric pressure since it concerned argon at pressures up to 80 atm and ruby lasers to generate and maintain plasma. However, it marked a forward step in terms of development of theory and the mechanism of the process.

The experiments were performed to determine the minimum powers of laser radiation necessary to maintain plasma under various conditions and to study certain properties of the resulting plasma, mainly its temperature. The initial plasma was created by air breakdown from another pulsed laser. The igniting ruby laser operating in a spiking, free-running, regime produces a 1.5-2 j pulse 0.3-0.4 msec, and average power of 5 Kw breaks down argon at the pressure of 10 atm, while the giant pulse would require about 800 Kw for the same pressure and approximately the same focusing system.

The basic consideration in these experiments was plasma temperature. This was determined mainly by the absorptive capacity of plasma relative to laser emission. At the relatively low pressure of 16 atm plasma is fairly transparent; it loses its transparency at 80 atm. At 16 atm the computed temperature was about 22,000°K, which is in fairly good agreement with the maximum measured temperatures of 18,000°K. At 80 atm the theoretical value is 25,000°K, which is below the experimental value of 33,000°K. Heat conduction losses weakly depend on pressure; the fact that at low pressures the threshold power sharply decreases with increasing pressure indicates that radiation losses are small. The threshold values

of power required for a ruby laser to maintain plasma in argon can be used to estimate the power necessary for a long-term maintenance of plasma under similar conditions by a continuous wave. CO_2 laser. Thus, it is estimated that at 10.6 microns the threshold power will be about 300 w. However, as noted above, experiments reported in [3] showed that given sufficiently sharp focusing, even 150 w was sufficient.

A paper that may be relevant to Rayzer's research was recently published by his well-known associate, B. Ya. Zel'dovich, and one of the co-authors of the works under consideration, B. F. Mul'chenko [12]. It reports on the feasibility of using a conical lens for focusing a laser beam to produce a long spark. An experiment was performed with a 15 Mw ruby laser beam passing through such a lens into a cell with argon at hig pressure. A solid spark line 30 mm long was obtained at 90 atm. The power density at the axis of the spark was computed to be about 2.10^9w/cm which exceeds the optical breakdown threshold for the case of a spherical lens at the same gas pressure. The authors note that the velocity of the breakdown front can reach very high magnitude and that a simultaneous dev ment of breakdown over considerable lengths is possible. Two advantages the conical lens are mentioned: (1) the breakdown sites do not prevent the light energy from reaching other points on the axis and (2) the rapi emission of energy at the axial caustic can be used to modeling linear explosions and cylindrical shock waves.

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II. EXPLOSIVE ELECTRON EMISSION

S. G. Hibben

The interest in the electrical insulating properties of high vacuum is due to a large extent to the recent requirements for high-voltage equipment which will make use of the vacuum environment of outer space. Explosive field emission phenomena are relevant to this interest and to some of the goals pursued in the study of electric explosion of wires and films.

A continuing series of Soviet studies has been reported in the last several years on phenomena of explosive field emission, generally produced by applying a fast-rise high voltage pulse to a sharply pointed metal electrode in vacuo. This results in currents on the order of kiloamperes, and a rapidly propagating plasma from the electrode tip. Prominent articles related to this subject include those of Mesyats et al [1,2], Bugayev et al [3,4], Kartsev et al [5], Kremnev et al [6], and Fursey et al [7,8,9]. These and their co-authors evidently compose a group studying the explosive effect of very powerful field emission, with most laboratory work being reported at both Leningrad State University and Tomsk Polytechnic Institute. Some reports on their most recent experience with explosive emission effects are discussed below.

A general summary of the discharge phenomena in question has been given by Mesyats and Proskurovskiy in [10]. For sufficiently large applied voltage pulses, field emission currents on the order of 10^3- 10^5a can be produced at the tip of a metallic needle cathode, followed by a local explosion at the tip owing to resistance heating by the current. For field gradients of 10^8 v/cm or more at the tip, the explosion will occur within a nanosecond following voltage application; the resulting plasma has been termed a cathode flare. In [10] the authors give some results of such a test using needle cathodes of W, Co and Cu, placed in vacuo 0.05 to 1 cm away from a planar anode, and subjected to square pulses of 10-500 kv with rise times on the order of a nanosecond. Pulse widths were varied from 5 to 50 nanoseconds, but in all cases were less than the time at which anode evaporation began. Tests show that currents of several kiloamperes were obtained, and that the flare expanded in a roughly spherical pattern at a velocity of about 2 x 10^6 cm/sec. A major

object in this test was to determine the nature of metal evaporation from the needle tip as a function of its initial dimensions and the number of pulses applied to it. Figure 1 gives two examples of profile degradation in a molybdenum needle. For tip radii of 10 microns it was found that electron emission occurred over an area about 10^{-6} cm^2, and reached densities up to 5×10^7 a/cm^2. Peak current during the discharge was from 1 to 3 orders greater than could be accounted for by the plasma, thus verifying that field emission was taking place from the cathode surface proper.

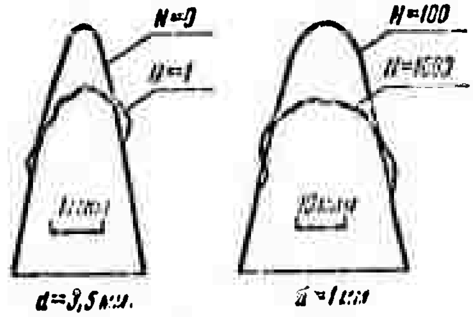


Fig. 1. Needle tip profile after applying N pulses of 30 kv, 10 nsec.

A theoretical evaluation of attainable emission currents indicates that an increase in perveance of the beam can raise the maximum current level. This was proved experimentally by applying two equal voltage pulses with some delay between, the first to precondition the interelectrode space by starting plasma formation. Currents recorded during the second pulse were then up to 8 times higher than for the single-pulse case.

(It is noteworthy that the foregoing work by Mesyats and Proskurovskiy was reported from the Siberian Branch of the Institute of Atmospheric Optics, in distinction to the previously cited sources.)

Another type of explosive emission experiment has also been reported early in 1971 by Bugayev et al [11], on explosive emission from dielectric surfaces. In the present case this was achieved by placing a tungsten needle tip on the surface of a $BaTiO_3$ wafer as shown in Figure 2, and applying positive or negative voltage pulses to the needle while simultaneously applying a +30 kv pulse to the anode. Spectral analysis of the generated plasma was used to determine the chronological order of material breakdown at the electrode-dielectric junction. The analysis consistently

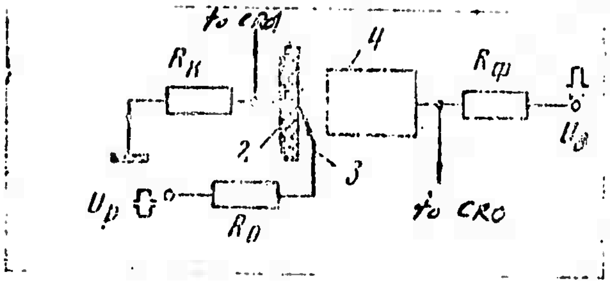


Fig. 2. Needle-on-dielectric explosion test.
1 - $BaTiO_3$
2 - electrode
3 - needle
4 - extractor

showed neutral and singly ionized Ba lines appearing prior to W lines (Table I) indicating that explosive action begins in the dielectric and is followed by ohmic-heating explosion of the metal tip.

Table 1

ORDER OF SPECTRAL LINE APPEARANCE
WITH VARYING DISCHARGE PULSEWIDTHS t_p

	Negative		Positive	
	tp=8ns	2 ns	tp=8ns	2 ns
Appearance of Ba I, Ba II lines	0.62 ns	1.4	0.8	1.18
Appearance of WI and other lines	0.8 ns	1.63	1.3	1.5

The findings agree with those of earlier reports, which indicate that current densities on the order of 10^9 a/cm^2 are required for explosion of the tungsten tip, which is 5 to 6 orders greater than that required for ceramic explosion. In this type of contact experiment, as the authors point out, the irreducible roughness in the needle tip and ceramic surfaces leads to local microgaps within their contact area, resulting in very high local current densities for voltage gradients on the order of only a few hundred volts/cm.

Another experiment by Mesyats et al [12] was designed to get a more exact picture of plasma propagation following the emission explosion. The test was specifically designed to correlate plasma kinetics with excitation pulse parameters and needle geometry, for the case of an exposed needle electrode in hard vacuum. The authors used an etched single-crystal tungsten needle with a tip radius of 3×10^{-5} cm as a cathode,

in a discharge tube held at 5 x 10^{-9} torr, with a grounded grid interposed 5 mm from the cathode. Collector current through the grid was monitored after explosive emission was induced by applying a large negative pulse to the cathode, at a rise time of 1 nsec, a 4 μsec duration, and amplitudes of 19-30 kv. In this case current flows to the collector until the plasma reaches the grid, at which time an arc condition obtains between cathode and grid and collector current is cut off. Thus a synchronized oscilloscope trace of collector current duration gives a precise transit time for the plasma to reach the grid, yielding its mean velocity. Graphical results obtained in this way are shown in Figure 3, giving plasma velocity as a function of voltage rise time at the needle tip. An effect

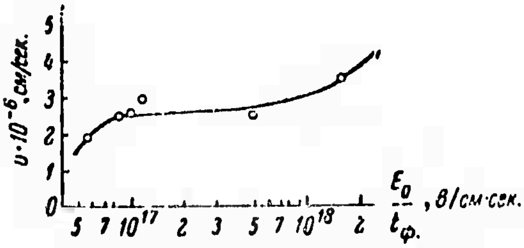
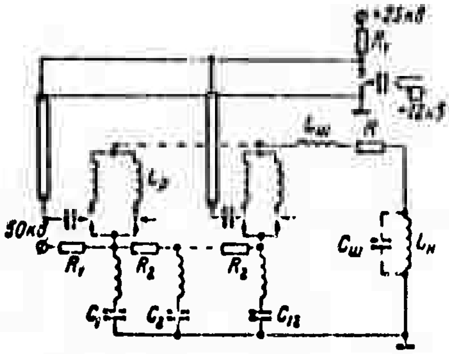


Fig. 3. Plasma velocity vs. voltage rise time.

of interest here is that, over an order of magnitude change in pulse rise rate, plasma velocity is effectively unchanged and remains in the 2-2.5 x 10^6 cm/sec range, which is consistent with the flare velocities reported by several other authors. This technique also allows adjustment of the explosion time with respect to the applied voltage pulse; thus in Figure 3 the left-most data point corresponds to an explosion occurring at the peak of the voltage pulse, whereas all other data points are for explosions occurring during pulse rise time. In the latter cases the current at the tip reached 50-60 a in the order of a nanosecond. Maximum energy of tungsten ions in the moving plasma was put at about one Kev.

The feasibility of all these experiments is of course dependent on the ability to generate a clean, high energy voltage pulse in the multi-kv range. This requirement involves a number of troublesome mechanical and electrical design problems which are the subject of considerable attention in the literature. Some form of a parallel condenser bank is typically used, with rather complex design methods employed to minimize internal and line inductance and resistance, mechanical stress during

discharge, and impedance mismatching in the interconnecting and output lines. A recent improved design of such a supply, designed for explosive element testing, is described by Baykov et al in [13]. The supply uses a bank of 12 capacitors, each of which has a parallel set of matched discharge gaps. The simultaneous output pulse from each pair is coupled to a common output coaxial pulse cable. Figure 4 shows the physical arrangement of the capacitors.



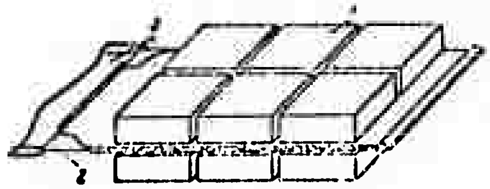


Fig. 4. Schematic and placement of discharge capacitors.

1 - capacitor
2 - high voltage bus
3 - ground bus

Individual capacitors are 2.5 μf at 50 kv working voltage; the combined array is rated at 40 kj, 10-50 kv, with an overall internal inductance of 12×10^{-9} h and resistance of 6.5×10^{-3} ohm. Particular design effort was expended in neutralizing the mechanical stresses associated with the high current discharge. Also, an order of magnitude decrease in impedance mismatch is claimed over existing multielement supplies of this type. An idea of the dimensions involved is given by the size of the common copper ground bus (3 in Fig. 4), which is 2.5 by 3 meters. The report generated by a discharge is evidently strong enough to warrant the use of acoustic absorbing material around the installation. In view of its simplified design and low mismatch error, the authors indicate the feasibility of further paralleling supplies of the cited type, to develop pulsed energies up to the 1 Mj range.

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III. SUPER-STRONG PULSED MAGNETIC FIELDS

A. Polushkin

Several publications [1-6] of G. A. Shneyerson (alone or with co-authors) of Leningrad Polytechnic Institute (LPI) appeared in 1970 on the subject of superstrong pulsed magnetic fields. These publications together with earlier papers [7-17] reflect the work done at LPI in pulse current technology based on capacitor storage systems developed to generate currents of up to several million amperes with period of 10^{-6} to 10^{-4} second at relatively low operating voltages (5 to 150 Kv).

This work has been stimulated by modern trends in experimental physics and industrial technology. It was particularly inspired by the problem of controlled thermonuclear fusion. Lately the pulsed strong current technique has gained impetus from other areas of application such as:

1) pulsed plasma acceleration for research and for space propulsion;
2) gas discharge pulse light sources;
3) nuclear physics and accelerator technology;
4) magnetic hydrodynamics; and
5) industrial technology (metal forming).

In some respects, this work also appears related to the U.S. research carried out in the Fifties and Sixties by C. M. Fowler et al (Journal of Applied Physics, v. 31, 588 (1960), v. 35, 781 (1964)) who considered implosion of metal liners, by R. L. Conger (Ibid., v. 38, 2275 (1967) who dealt with explosion effects, and others. Similar work on explosive compression of magnetic fields by shaped charges placed around metal cylinders was also done earlier by S. Lukasik and S. Koslov (private communications). The Soviet research reported here, however, deals with magnetic implosion and explosion effects without the use of high explosives.

For a number of years Shneyerson was specializing in the development of heavy-current short-pulse solenoids; he is the author of a considerable body of theory dealing with solenoid geometry and magnetic field structure and is credited with numerous exact solutions for single-turn, thin- and thick-walled coils, complex field configurations, and extreme mechanical stresses [6, 7, 8, 10, 13, 16, 17]. In his recent work

he has concentrated on the explosive mechanical effects of high magnetic fields.

The value of B_m is determined for the case when the effective inner radius of the solenoid increases noticeably before the current reaches its amplitude value I_m. Under such conditions, B_m is considerably smaller than its calculated value. Three mechanisms of the effective inner radius increase are considered:

1) metal flow in the radial and axial directions caused by the magnetic pressure, which can be described by an approximation of an ideal incompressible fluid,
2) field diffusion into the conductor, and
3) electric explosion of the skin layer.[1]

Shneyerson concludes from the analysis that, at very large initial current time rise $(di/dt)_o$, the quantity B_m for all three models increases proportionally to $(di/dt)^{1/2}_o$ for any of the three growth mechanisms. This amplitude depends only slightly on τ (the current time rise), ρ_o (specific resistance) and γ (material density) and is independent of r_o, the initial value of the inner radius.

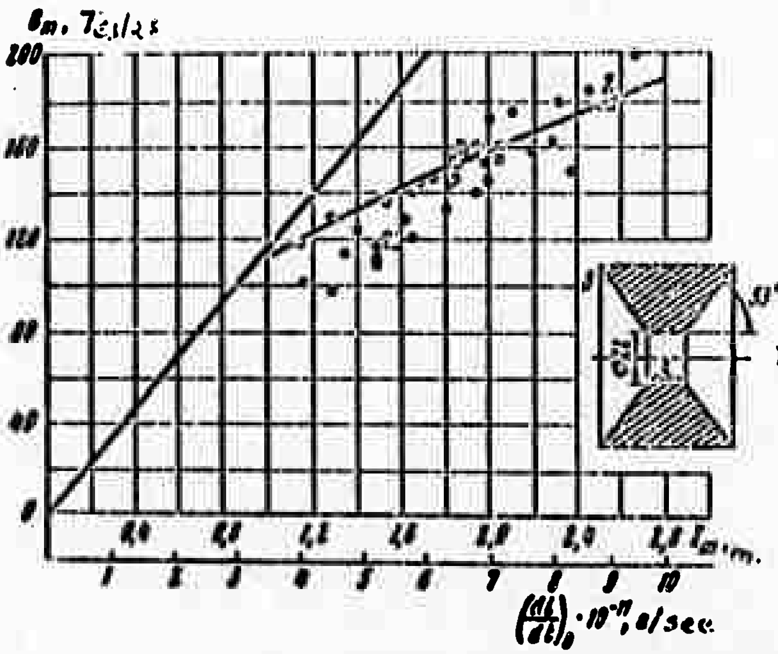

Fig. 1.

ooo - experiment;
1 - model measurements;
2 - $B_m = 0.53\ \gamma^{1/4}\ \mu^{3/4}\ (\frac{di}{dt})_o^{1/2}$
3 - solenoid cross-section

Fig. 1 shows the results of measurements of B_m in copper (C=0.53) solenoids with an internal radius r_o=1.7 mm and l_o=3/2 r_o. The rate of radius expansion was 400 to 600 m/sec; current rise time τ = 11.5±0.2 μsec.

The rapid constriction of thin-walled metallic cylinders in a strong pulsed magnetic field is the subject of two recent Shneyerson papers [2, 4]. Interest in this subject was associated with the generation of strong magnetic fields by flux compression, with the production of strong pulsed pressures and with the study of the energy transformation processes in complicated electromagnetic systems with variable parameters.

In his theoretical treatment [2] he considers the compression of an ideally conducting thin-walled cylinder and assumes instant and lossless current transfer from the storage system to the load to derive an expression for the constriction time for general and limiting cases.

In an experimental study of the process [4] over a wide variation of typical parameters two types of single-turn solenoids were used (100 mm long, 75 and 100 mm in diameter). A capacitor battery C_o=12.8 μF with maximum stored energy W_o=92 kj was discharged through a 14:1 pulse transformer into a solenoid. The inductance of the discharge circuit was 0.075 μh (frequency of the discharge of about 10 kHz). In order to obtain a larger variety of deformation models, the experiments were conducted at various initial battery voltages U_o ($40 \leq U_o \leq 120$ kv).

Instantaneous values of cylinder radius were recorded with an SFR high-speed camera (125,000 and 250,000 frames/sec.). Typical time dependences of the sample radius variation obtained from the SFR-grams are presented in Figs. 2 and 3. Instantaneous configurations of the sample inner contour in Fig. 2 indicate that deformation takes place symmetrically down to the time when the radius reaches half of its initial value. Continuing the process further usually leads to destruction of the sample.

Shneyerson together with V. P. Knyazev conducted a similar investigation of the rapid expansion of thin-walled metallic cylinders under the action of strong pulsed magnetic pressure [3]. This type of short period loads is analogous to an explosion. Research on rapid deformations of this type is interesting both from the point of view of the various types of applications (problems of the strength of solenoids and the plastic deformation of metals) and from the point of view of the dynamics of inelastic deformations.

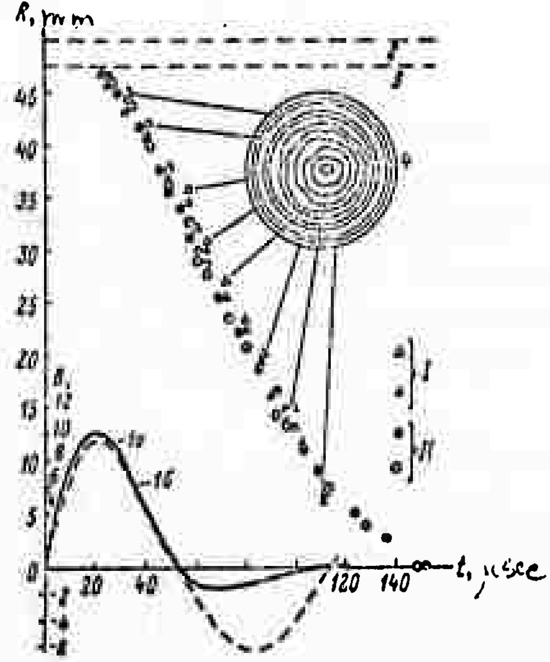

Fig. 2. Constriction of type 1 samples. Change of cylinder radius with time: I - at an oscillatory discharge of U_0 = 80 kv; II - at unipolar pulse; 1a, 1b are variations of the magnetic field for the oscillatory discharge and unipolar pulse respectively; 2 is the inner radius of the cylinder; 3 is the external radius of the cylinder; 4 represents the instantaneous values of inner cylinder contour.

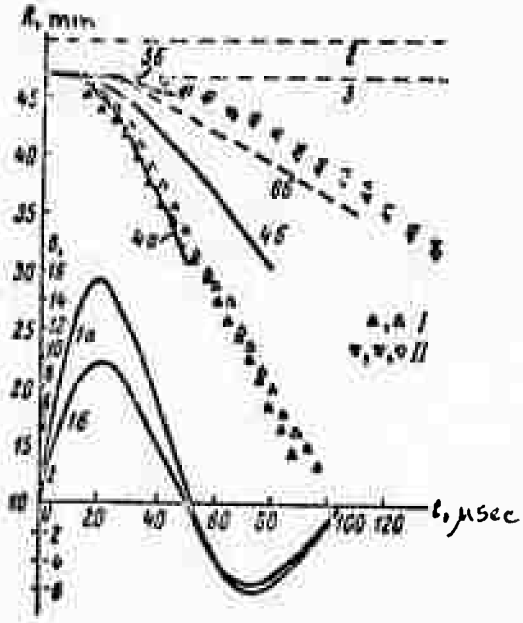

Fig. 3. Comparison of experimental and computed values for type 3 sample at different initial capacitor bank voltages. I - 120 kv, II - 60 kv; a - 120 kv, b - 120 kv; 1 - variation of the external magnetic field with time; 2 - inner radius of the solenoid; 3 - initial cylinder radius; 4-6 - calculated radius variation.

In the experiment described, the expansion of thin-walled cylinders made of aluminum alloy is studied within a wide range of velocities ($50<v<410$ m/sec.) for radius change, with simultaneous measurement of the magnitude of the magnetic field. Motion in a number of such cases substantially differed from purely inertial motion. Oscillograms of the magnetic field were used to determine the instantaneous value of force and to calculate by computer the course of deformation. A comparison is made between experimental points and the computed curves for the displacement of the cylinder walls for various models which describe the deformation. The best approximation to experimental values in the range of deformation values under study ($\dot{\epsilon} = 10^3$ to 10^4 sec.$^{-1}$) is given by the model of an elastic-viscous body (the Maxwell model).

The process of converting the energy of the strong pulsed magnetic fields obtained by capacitor discharge into the kinetic energy of an accelerated conductor or into the potential energy of its deformation is analyzed in [5]. Of particular interest is the dependence of the conversion efficiency on the basic parameters of the discharge circuit and of the accelerated body. The numerical integration of the transient process equations was done by computer. Several systems are investigated: 1) a system with inductance varying linearly with respect to the motion coordinate; 2) axially symmetric constriction and expansion of a cylinder by an azimuthal field; and 3) axially symmetric constriction of a cylinder in a longitudinal field. It has been established that energy conversion efficiency depends on the parameters $k = L_o'C^2U_o^2/2m\Delta L$ and $\varepsilon = \Delta L/L_o$, where L_o - initial inductance, ΔL - inductance change, C - capacitance and U_o - initial voltage of the capacitor bank, m - the mass of the accelerated body, and $L_o' = \mu_o l/2\pi x_o$ (l - axial length of the system, x_o - initial radius of the cylinder).

The process of acceleration is most effective if it occurs during the first half period of current change in the circuit at $k \simeq 1$. This conclusion is valid for all the variants of the examined geometry. At decreasing initial inductance of the circuit L_o, acceleration efficiency at first increases, and then decreases slightly, i.e., for each actual

condition there exists a definite optimum nonzero value for L_o. The ohmic resistance of the circuit affects more strongly the efficiency of slow processes, for which $k < 1$. The degree to which resistance affects efficiency when $k \geq 1$ is determined by the decrease of the first maximum of the current in the same way as occurs in an oscillating circuit with constant parameters.

Shneyerson's activity includes also the development of high-voltage technology equipment. Two pieces of such equipment are presented in the literature as outstanding examples of this work.

THE LPI PULSE CURRENT GENERATOR (PCG) [6]

This generator was developed and constructed in the laboratory of high voltage technology of LPI. Its basic circuit is presented in Fig. 4 and it has the following basic parameters:

Energy, kj	1000
Operating voltage, kv	150
Total capacitance, μf	92
Current rise time (T/4), μsec	2.5
Maximum current amplitude (at short circuit), Ma	8.0
Stray inductance, nh	40.0
Number of parallel connected spark gaps	42

The generator consists of 42 sections, each containing four KMM 150-0.6 capacitors with an internal inductance 0.25μh, one commutating spark gap of a trigatron type and four coaxial cables of the ST-4 type (15 m long, 95 mm^2 core cross section, running inductance 130 nh/m) connecting the section to the central busbars of the generator.

A general view of a single section is presented in Fig. 5.

The synchronous operation of the generator spark gaps requires that firing voltage rises to 40-50 kv in about 20 nsec. This is assured by a special low-inductance firing generator, which has the following parameters: four low-inductance capacitors 0.5 μF each with operating

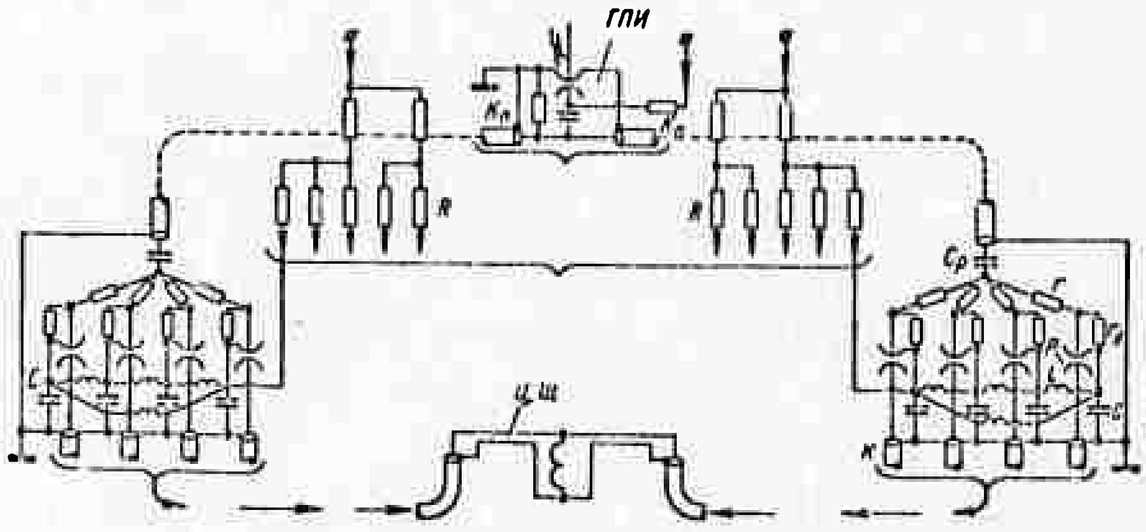

Fig. 4. Basic circuit of the LPI pulse current generator (PCG), 150 kv, 1 Mj

C - Four capacitors КИМ 150-016 (total 168 capacitors); P - controlled spark gap (altogether 42 spark gaps); K - SI-4 coaxial cable, one for each capacitor (total 168 cables); ЦШ - central busbars with the load; ГПИ - generator of firing pulses 25 kv, 2 μF; K_n - firing cable, two or three PK-3 cables 25 m long each, one for each three-four sections (total 30 cables); C_p - dividing capacitor (150 kv, 0.002 μF), one for three-four sections (total 12 capacitors); r - resistor 120 ohms; r_y - leakage resistance; R - charging resistors 10 kΩ, one resistor per four sections; L - charging reactance choke (10 μh, 2Ω).

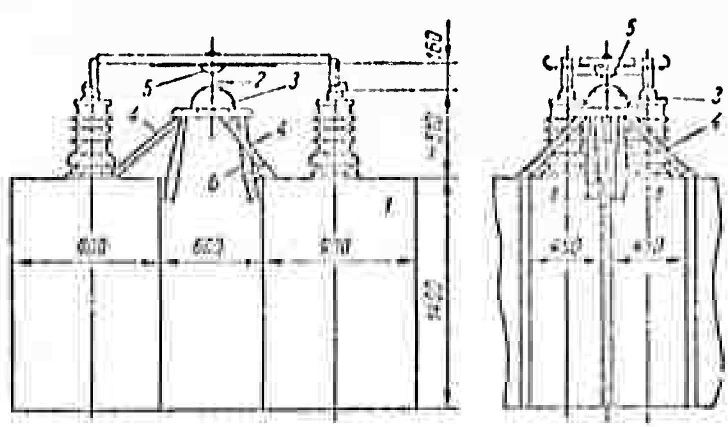

Fig. 5. A section of the pulse current generator (150 kv, 1 Mj)

1 - Capacitor case; 2 - spark gap; 3 - lower electrode of the spark gap; 4 - supporting insulators; 5 - upper electrode of the spark gap; 6 - cable.

voltage 25 kv and with stray inductance under 50 nh (see Fig. 4); the generator discharges into 36 firing cables of the PK-3 type 25 m long and with characteristic impedance 75 Ω each. At the firing of generator the firing pulse is applied to the control electrode of the spark gap through the dividing capacitors (one for four spark gaps) and an active resistor. The end terminal mismatch of the firing cables increases the voltage of the firing pulse up to 50 kv.

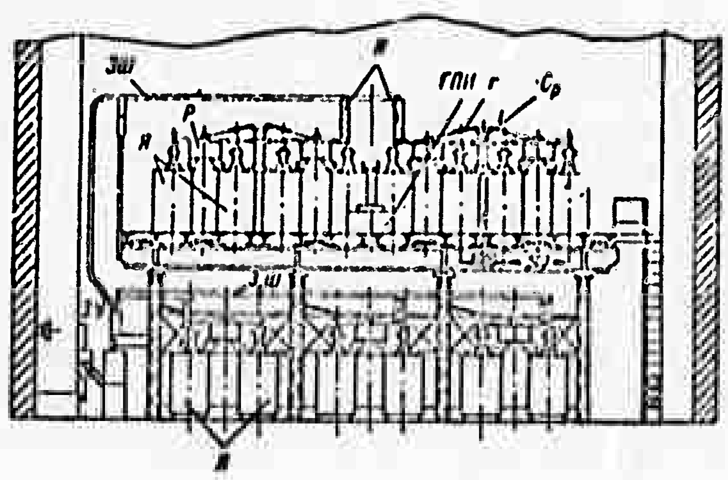

Fig. 6.

THE LPI STEP-DOWN CABLE TRANSFORMER FOR STRONG PULSED CURRENTS [6,11]

Not satisfied with the performance of the commonly used transformers (H. P. Furth et al, Rev. Sci. Instrum., 1957, 28, 949) the LPI undertook development of a transformer with optimized parameters.

The following performance data of the transformer described in some detail below were obtained during a test at 100 kv on a capacitor battery of 28.5 µF:

Secondary short circuit current, a	3×10^6
Short-circuit inductance of the transformer (reduced to the secondary), nh	17
Including leakage inductance, nh	12
Magnetization inductance, nh	360
Resistance (reduced to the secondary), ohms	4×10^{-4}

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IV. LASER INDUCED HIGH TEMPERATURE SUPERCONDUCTIVITY Y. Ksander

Twenty-four elements in the periodic table have been found to be superconducting [1]. The highest transition temperature -- 9.3°K -- is that of niobium, although higher temperatures (~21°K) have been achieved in an alloy of niobium with aluminum and germanium [2]. Efforts to advance further the transition temperature by alloying impurity-doped superconductors have not been successful. A greater degree of success in this field has been achieved -- notably at the Department of Low-Temperature Physics of the Moscow State University -- through the application of high pressures (up to 200 kilobars) to certain metals and alloys at ultra-low temperatures down to a few hundredths of a degree K [1]. Intended largely for testing the existing BCS theory, the high-pressure studies profess near-term (5-10 years) possibilities for the creation of new superconducting modifications of elements and compounds at higher temperatures. The achievement of temperatures higher than $T_c \lesssim 30$-40°K by means of conventional methods (new alloys, modifications) appears to be precluded by the phonon mechanism itself [2]. Although considerable uncertainty still beclouds the non-phonon mechanisms, high temperature (80-300°K) superconductivity produced by the bound electron-hole pairs (excitons) -- a non-phonon mechanism -- has received serious consideration in recent years [2,3].

Ginzburg, the unofficial dean of the Soviet research on superconductivity, adheres to the latter and tends to favor so-called "sandwich" elements -- metallic film clad on both sides with dielectric, semiconductors [2]. Although he feels strongly about his exciton theory, he admits that in the development of high T_c superconductors, the surface has barely been scratched and he welcomes research in this area along lines which are different from his.

Also in recent years (1968-1970), interest was evinced in studying the effect of an optical field on the superconducting properties of crystals [4-7]. Two studies -- one Indian [4] and one Soviet [5] -- consider theoretically single-electron models of a superconductor in a resonant optical field in which the electron-hole pair forms a bound

state due to a two-boson exchange. The work from India [4] raises some doubt -- in Blazhin's mind [7] -- as to whether it deals with the superconducting state, although the authors clearly formulate expressions for the superconducting energy gaps and the transition temperature (estimated to be 100°K).

Blazhin's model -- for which he derives the interaction Hamiltonian and uses suitable canonical transformations -- consists of a heavily doped semiconducting crystal with a parabolic conduction band whose (non-absolute) minimum coincides with the center of the Brillouin zone [7]. The electron concentration in the conduction band remains invariant under the optical field and direct transitions are nonexistent due to the width of the forbidden gap (E_G) being greater than the incident photon energy ($\hbar\omega$). The indirect transitions are sufficiently forbidden.

In such a model, Blazhin contends, the optical field induces strong polarization of the valence electrons due to the Coulomb interreaction between interband -- valence and conduction -- electrons. This results in the heating of the latter and their subsequent pairing.* The free electrons and holes in such a model also interact with the optical field and form Cooper pairs. Under certain conditions, these processes will lead to -- Blazhin claims -- the occurrence of high T_c superconductivity.

The width of the energy gap of a superconductor (temperature T=0) is given by

$$\Delta(0) = 2(E_G - \hbar\omega)\, e^{-\frac{1}{F_1 F_1}}, \qquad (1)$$

---

*That electron polarization leads to the needed Cooper pairing of electrons raises some doubt that superconductivity will occur at all, let alone at an increased temperature. The use of opposed laser beams giving electron polarization in two directions is postulated as an additional parameter needed for pairing [8].

where F is the interaction constant and

$$F_1 = \frac{\nu}{2\pi}\left(\frac{3}{\pi}\right)^{1/3}\left(\frac{Sd}{E_G - \hbar\omega}\right)^2\left(\frac{E_G - \hbar\omega}{\hbar\omega}\right)^{1/2}\left(\frac{R}{\hbar\omega}\right)^{3/2} n^{1/3} a_0 \left(\frac{m_k}{m_p}\right)^{1/2} \times$$
$$\times\left\{\left(\frac{m_p - m_k}{m_k}\right)^2\left(\frac{1}{2} + \cos^2\theta - \frac{1}{8}\cos^4\theta\right) + \right.$$
$$\left. + \frac{m_p}{m_k}\,\frac{E_G - \hbar\omega}{\mu}\,\frac{5}{3}\left(\cos^2\theta + \gamma\sin^2\theta\right)\right\}, \qquad (2)$$

where $\gamma = 1$

$R = e^4 m_k/\hbar^2\chi^2$ is the Rydberg constant

$a_o = \hbar^2\chi/m_k e^2$ is the Bohr radius

χ is the permitivity

ω is the electron concentration at the K minimum

m_k, m_p are the effective masses of electrons at the different minima

θ is the angle from the direction of polarization of the optical field

ν is the number of minima in a semiconductor

The transition temperature is given by

$$T_c = 0.577\Delta(T = 0) \qquad (3)$$

Blazhin's numerical calculations using the above relationships have led him to some interesting results. Assuming a laser intensity of $E \approx 10^5$ v/cm, $\hbar\omega \sim 0.5$ ev, $\chi \sim 5$. $n \approx 10^{19}$ cm^{-3}, $m_p \sim m_o$ and $m_k = 0.01m_o$ (where m_o is the mass of a free electron) and $\nu = 6$, the calculated value of F is ~ 0.4. The latter is on the order of the value obtained for the phonon mechanism. Considering that $E_G - \hbar\omega \sim 0.1$ ev, the energy gap yields a value which is sufficient to sustain superconductivity at $T_c \sim 100°$K.

Objections which are normally raised against the heating of the free electrons in the laser field are, in Blazhin's opinion, not serious and can be surmounted by using heavily doped semiconductors -- including p-type -- with a narrow gap ($\hbar\omega$ > gap width) [9]. By far a more serious problem is the possibility of extinction of superconductivity by means

of optical-field-assisted transfer of carriers across the energy gap Δ. However, this problem can also be circumvented by careful localization of the optical field.

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V. OPTICAL EXPLOSIONS S. G. Hibben

The interaction of intense laser radiation with a variety of target materials is receiving increased attention in leading Soviet research activities. In the last two years alone at least 160 articles have been published by Soviet physicists on phenomena of intense laser beam reactions with gaseous media, metals, dielectrics, semiconductors and liquids [1]. The most advanced research on this subject is being reported at the Lebedev Institute by N. T. Basov, O. N. Krokhin, G. A. Askar'yan, I. N. Arutyuyan, M. M. Savchenko, and several others. In [2], for example, Basov et al give an extensive treatment which is the most comprehensive summary of Soviet experience to date on laser plasma dynamics. More detailed analyses of some effects peculiar to laser explosions have been recently attempted by Askar'yan et al, several of whose reports are examined herewith.

DIAMAGNETIC MOMENT

The appearance of a diamagnetic moment in a laser-generated plasma within an external field has been previously reported by Askar'yan et al [3-6] but Askar'yan has recently concluded that the explanations offered so far for this field rejection phenomenon have been oversimplified and require a more detailed treatment [7]. To do this it is necessary to relate the diamagnetic moment more exactly to other physical parameters of the optical spark interval; in particular, Askar'yan pursues the question of why the diamagnetic moment persists well beyond the energy input interval, and what factors govern this behavior.

In [7] Askar'yan et al describe a series of experiments in which pulsed laser radiation was focused in various gases within a pressure vessel, while the resulting plasma generation and magnetic field behavior were monitored. A high-power Q-switched laser was focused through a chamber window into a wide variety of gases, including air, N_2, O_2, H_2, D_2, CO_2, SF_6, and the noble gases, at a wide range of initial static pressures. External fields up to 10^4 oe were simultaneously applied in the region

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of the focal point, with an inductive pickoff coil placed around the focal region to register local suppression of the applied field following an explosion. Pickoff coil radii were from 3-6 mm, insuring that the coil area was large compared to the diamagnetic region. Absorbed optical energy was also monitored by a calorimeter method, while the incident energy was varied by means of filters.

The main object of this experiment was to find the dependence of the generated diamagnetic moment M on incident energy E absorbed in the spark at various densities ρ, for each of the tested gases. Tests showed a nearly linear dependence of $M(E/\rho)$ for all gases, irrespective of the wide range of laser energies and gas densities (more exactly, $M(E/\rho)^{1.2}$). Furthermore, M was directly proportional to the mass of the ion or atom in question. Some effort was also made to identify the limits of the diamagnetic perturbation region by moving the pickoff coil along the axis of the spark; this was apparently most successful for krypton, in which the spark was exceptionally large and bright, with a predictably extended diamagnetic region. The behavior of M was also investigated as a function of the dimensions of the spark region and of the geometry of the incident laser beam; however, it was again confirmed that M was dependent only on E, regardless of the variations in these parameters.

From these experiments, Askar'yan postulates the following model for the diamagnetic phenomenon in high-temperature shock waves. The diamagnetic perturbation is caused by eddy currents generated by motion of conducting layers in the medium behind the expanding shock wave. Initially, the dimensions of the perturbation region may approach those of the shock wave; with expansion and decreasing temperature at the shock wave front, the eddy current region becomes confined to the interior higher temperature region, in accordance with the assumed inverse temperature gradient from the shock wave front back to the energy release point. The question is then to relate the lifetime of the perturbation region to penetration of the external magnetic field and to shock wave radius r_{sh}. Askar'yan does this rigorously in [7] showing that the magnetic parameters have an almost negligible dependence on r_{sh}, i.e., on time, for a sufficiently hot spark.

He goes on to show that the external field can, in fact, be made the dominant factor in determining diamagnetic lifetime in the plasma, regardless of the stage of plasma development.

Some other interesting effects are also briefly mentioned by Askar'yan in these tests, in which the primary shock wave is reflected off of a focusing surface back onto the plasma. This technique suggests some possibilities for confining the detached fireball behind the primary wave, or for confining plasma propagation in general.

INITIAL STAGE PHENOMENA

A subsequent paper by Askar'yan and Tarasova [8] again attempts a more rigorous analysis of some optical explosion phenomena. Attention is concentrated here on the very early stages of plasma generation from powerful laser impact on a solid, i.e., the period during which the size of the exploded volume of matter has not yet exceeded the dimensions of the incident laser beam.

For their analysis the authors assume a simplified physical model in which total energy absorption occurs in the initially dense plasma, which is justified on the basis of known strongly nonlinear absorptive behavior to very powerful ultra-short laser pulses. In view of the resultant high electron thermal conductivity and small initial plasma dimensions, one may also safely assume an even temperature distribution throughout the plasma at this stage; furthermore, the short time interval involved permits the assumption of no radiant heat loss from the plasma.

With these qualifications the authors use energy balance methods to arrive at a characteristic initial expansion velocity v_0 which depends only on incident flux density and initial material density. For example, for a laser power of 10^{12} W and a focused spot diameter of 10^{-2} cm, flux density is 10^{23} erg/cm^2 x sec and $v_0 = 10^8$ cm/sec, corresponding to a divergence energy on the order of 10 kev. It follows that in this interval the thermal energy is far greater than the kinetic energy of dispersion. Askar'yan also arrives at an interesting conclusion, namely that during a subsequent interval the plasma radius and velocity increase at an exponential rate, which is untypical of exothermic gas dynamics.

From his analytical results in [8], Askar'yan concludes that the described initial interval is the most significant in plasma development from laser pulses on the order of a picosecond; in fact, he characterizes the later stages of plasma expansion in such cases as trivial.

LINE-FOCUSED BEAM

The foregoing studies all assume a point or spot-focused laser beam. A departure from this is considered by Askar'yan and Stepanov in [9], where they briefly describe beam-target experiments using a two-dimensional or slit-shaped incident beam, formed by cylindrical rather than spherical lenses. In the tests cited a Q-switched neodymium laser with a 6 cm cylindrical lens was used to produce an extended optical breakdown in argon and other gases at pressures up to 20 atm; an unswitched laser was also used to form slits in metal targets. An inherent advantage of this method is that the focused beam area attainable with a cylindrical lens is substantially greater than that for a spherical lens -- by a factor of 100 in the cited case.

This paper mostly emphasizes the practical arguments for line-focused beams in material processing; however, in the case of line breakdown in gas or on a dielectric surface, it is also pointed out that plasma propagation velocity can exceed light velocity, which suggests a number of interesting theoretical and practical possibilities.

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